

# Observations of the Soft Gamma-Ray early Afterglow emission from Two Bright Gamma-ray Bursts.

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**Abstract.** We present the results of observations of the soft gamma-ray early afterglows with the energy above 100 keV from two bright Gamma-ray bursts detected by the PHEBUS instrument of the GRANAT orbital observatory. We show that the light curves of GRB 910402 and GRB 920723 events present the afterglow emission with fading fluxes. During our observations ( $\sim 700$  s) for these gamma-ray bursts the afterglow emission was fading as the power law of time with indices equal to  $-0.70 \pm 0.04$  and  $-0.60 \pm 0.05$  (at  $1\sigma$  confidence level). In both cases just after the end of the GRB event we observed the energy spectrum of the afterglow emissions which was softer than the energy spectrum of the main GRB events. The average photon index of the main GRB event (in 100–800 keV range) is equal to  $\sim 1.5$ . In the beginning of the afterglow emission the energy spectra of both events correspond to the much softer spectra with the photon index of  $\sim 2.5$ . We found that the times of abrupt softening of the burst spectra correspond within statistical errors to the moment when the afterglow emission begins to dominate over GRB emission. We found that during the afterglow emission of GRB910402 the statistically significant hardening of its spectra was observed. This is the first observation of hardening of GRB afterglow emission. Analysis of GRB 910402 and its afterglow showed that this GRB source emits during  $\sim 700$  s of our observations in soft gamma-rays (100–500 keV) only  $\sim 1.6\%$  of its total energy released during the main event. For the GRB 920723 we found that in afterglow during  $\sim 700$  s of our observations  $\sim 6\%$  of the GRB total energy was released.

**Key words:** Gamma rays: bursts

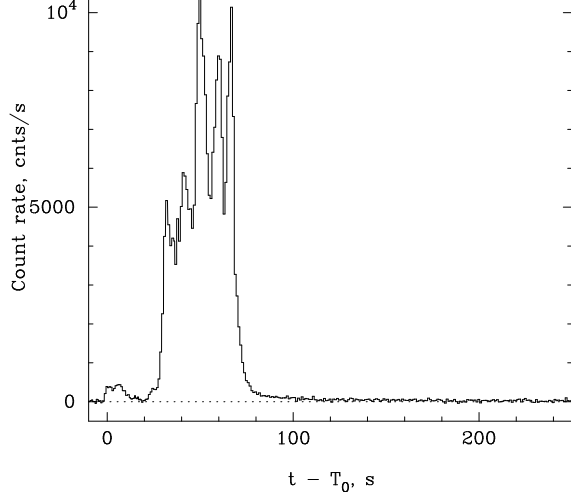
## 1. Introduction

Recent observations of the X-ray, optical and radio afterglow emission (e.g. Costa *et al.* 1997; Van Paradijs *et al.* 1997; Frail *et al.* 1997) of Gamma-Ray Bursts as well as measurements of the high redshifts of the GRB sources in optical give a new impact to the gamma-ray burst astronomy. It was shown that the sources of some of the detected GRB events are located at cosmological distances. X-ray and optical afterglow emission is fading as power law of time. Such behaviour is consistent with the relativistic fireball model of GRB (Mészáros&Rees 1993, 1997).

The results of earlier observations indicated that afterglow might be present right after gamma-ray burst events in x-rays (Sunyaev *et al.* 1990, Murakami *et al.* 1991, Terekhov *et al.* 1993, Sazonov *et al.* 1998), soft gamma-rays (Klebesadel 1992, Tkachenko *et al.* 1995), gamma-rays (Hurley *et al.* 1994).

The GRANAT observatory was launched into a high-apogee orbit with the PROTON carrier rocket on December 1, 1989. Its four-day orbit with an initial 200000 km apogee is of the kind that the satellite enters the Earth radiation belts only for a short interval (several hours). The satellite was outside the Earth magnetosphere and the radiation belts during 3 days in every orbit. This ensures almost constant background level during observations in absence of bright solar flares.

The PHEBUS instrument is the part of the payload of the observatory. It consists of six cylindrical (7.8 cm in diameter and 12 cm in height) BGO detectors surrounded by a plastic anticoincidence shield to reject the background connected with the charged particles. The detectors were placed on different sides of the GRANAT satellite, parallel to the axes of the Cartesian coordinate system in such a way that with the probability of 95% at least two detectors were able to observe a GRB event with no absorption by the satellite mechanical structure. The



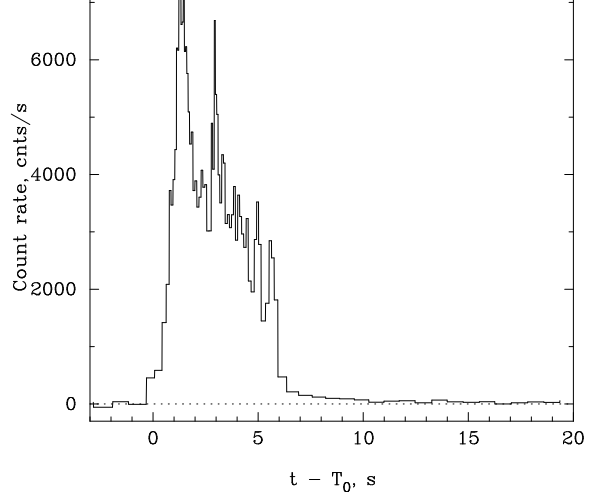
**Fig. 1.** The light curve of GRB 910402 in the 100–500 *keV* energy range.  $T_0 = 14^h27^m44^s.13$  UT.

instrument was sensitive to photons in the broad 100 *keV*–100 *MeV* energy range with the intrinsic total efficiency to gamma-rays equal to or greater 0.78. The field of view of the instrument was  $4\pi$  *ster*. Each of the six BGO detectors was equipped with a trigger system to detect bursts. The trigger system activates electronics of the instrument to transit to the “burst mode” automatically if the count rate exceeds the background level by at least 8 standard deviations, in at least two PHEBUS detectors.

We present the results of observations of the soft gamma-ray early afterglows with energy more than 100 *keV* from two bright Gamma-ray bursts GRB 920723 and GRB 910402 detected by the PHEBUS instrument. Both gamma-ray bursts are strong events and give statistically significant count rate in all 6 detectors of the PHEBUS instrument. GRB 910402 is the brightest burst observed by PHEBUS. The burst Universal trigger time is  $T_0 = 14^h27^m44^s.13$  UT. Fig.1 shows the background-subtracted GRB 910402 light curve in 100 – 500 *keV* energy range.

GRB 920723 has been detected by three instruments of the GRANAT observatory: SIGMA, WATCH and PHEBUS in 8 *keV* – 24 *MeV* energy range (Terekhov *et al.* 1995). For this burst the WATCH instrument detected fading 8 – 20 *keV* afterglow emission for more than 40 s after the end of the main event (Terekhov *et al.* 1993). Further analysis of the SIGMA data revealed soft gamma-ray afterglow lasted for  $\sim 1000$ s. The abrupt change of the GRB spectra was observed during transition to the afterglow emission in the 8 – 200 *keV* energy range (Burenin *et al.* 1999). The PHEBUS burst Universal trigger time of this event is  $T_0 = 20^h03^m08^s.3$  UT. In Fig.2 the background subtracted light curve of GRB920723 is shown in 100 – 500 *keV* energy range.

BATSE did not see either of these events. GINGA has an event at that time on 910402 and PVO did see GRB920723 (Fenimore 2000).



**Fig. 2.** The light curve of GRB 920723 in the 100–500 *keV* energy range.  $T_0 = 20^h03^m08^s.3$  UT.

## 2. Observation of the early afterglow emissions in GRB 910402 and GRB 920723

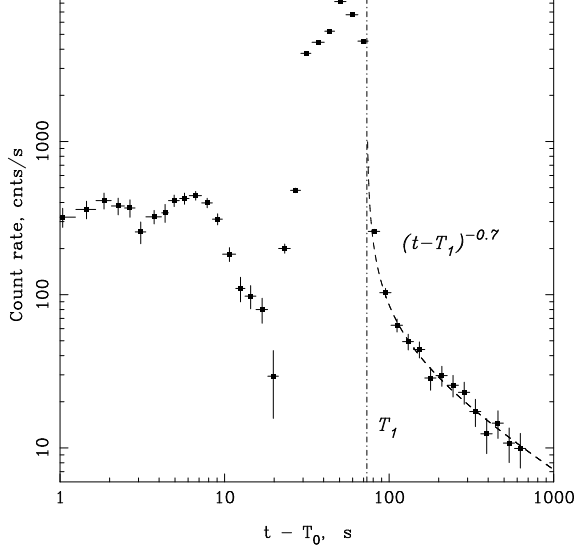
During detection of these two gamma-ray bursts the GRANAT satellite was outside of the Earth radiation belts and the Earth magnetosphere. There were no solar flares during these gamma-ray bursts (Solar Geophys. Data). Detailed analysis of the gamma-ray light curves shows that the fluxes after the end of the main events are not decreased to the background level during several hundreds of seconds. The background subtracted time histories of these two bursts in 100 – 500 *keV* energy range in logarithmic scale are presented in the Fig.3 and 5.

Investigating behaviour of the time history after the end of the the main gamma-ray burst we found that in all 6 detectors the count rate is varying around decreasing as the power law of time average values with the standard deviation correspondent to the Poissonian distribution. The trend of the count rate after these two bursts can be described by the same law (1) for  $t > T_1$ .

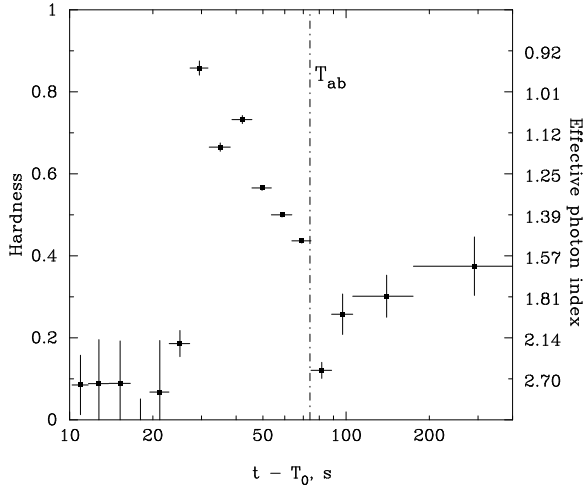
$$N(t) = I(t - T_1)^\beta \quad (1)$$

Using this simple model it is possible to define intensity of the afterglow emission  $I$  and power law index of time  $\beta$  for each of six PHEBUS detectors. It was also possible to estimate  $T_1$  - time when the afterglow emission fading as the power-law with time begins to dominate over the gamma-ray bursts emission.

We have found that the excessive (over background level in each of the six PHEBUS BGO detectors) count rates  $I$  were proportional to the intensities of the main GRB events in each detector as it had been expected in the case if the afterglow emission is really connected with gamma-ray burst source. For each of the bursts the  $\beta$  parameter was equal within statistical errors for all detectors of the instrument.



**Fig. 3.** The light curve of GRB910402 in 100 – 500 keV energy range in logarithmic coordinates. The instrumental background is subtracted.  $T_1$  corresponds to the best fit estimate of the beginning of the afterglow emission. The dashed curve corresponds to the law (1) for which the afterglow begins at moment  $T_1$ . Note that power line is curved in Log-Log space because the beginning of coordinates in this figure ( $T_0$ ) differs from moment  $T_1$ .



**Fig. 4.** The evolution of hardness of GRB 910402 (The ratio of the count rates in 250 – 800 keV to 100 – 250 keV energy ranges). The values of effective photon index on the right axis corresponds to the hardness values (left axis) for the power law spectra.  $T_{ab}$  corresponds to the moment of the abrupt softening of the emission from GRB source.

We have found that for GRB910402 the best fit corresponds to  $\beta = -0.70 \pm 0.04$  (at  $1\sigma$  confidence level) and  $T_1 = 73.2$  s ( $\chi^2/dof = 2.4/10$ ). The  $1\sigma$  confidence interval for  $T_1$  is from 62.2 to 77.9 s. To obtain these parameters we have used the afterglow count rate data from 85 to 700 s after  $T_0$ .

For GRB920723 the best fit corresponds to  $\beta = -0.60 \pm 0.05$  (at  $1\sigma$  confidence level) and  $T_1 = 6.1$  s ( $\chi^2/dof = 4.8/9$ ). The  $1\sigma$  confidence interval for  $T_1$  is

the afterglow count rate data from 8 to 700 s after  $T_0$ .

The energy spectra of the main bursts and afterglow emission are different. In both cases (GRB 910402 and GRB 920723) just after GRB event the energy spectrum of the afterglow emissions is much softer than the energy spectrum of the main GRB events. Fig. 4 and 6 show the evolution of the spectral hardness of the bursts. We define spectral hardness as the ratio of count rate in 250 – 800 keV to 100 – 250 keV count rate. We define the effective photon index as the index of a power-law spectrum (in the 100 – 800 keV energy range) which, would produce the observed hardness at an incidence angle of  $90^\circ$  to the detector axis.

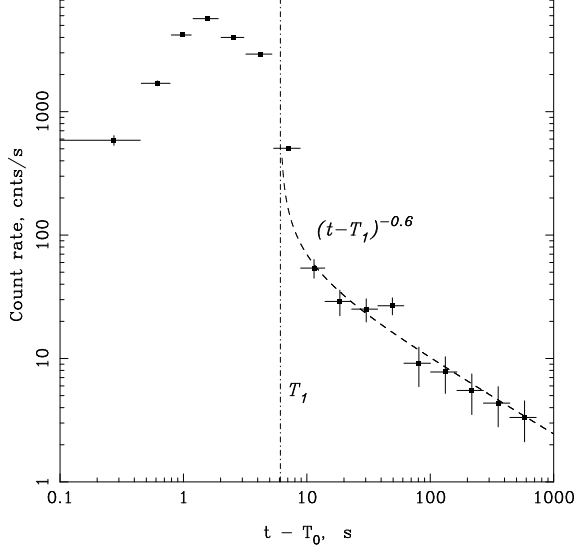
At the end of the both bursts the spectral hardness ratio is equal to  $\sim 0.4 - 0.5$  (fig.4 and 6). This corresponds to the photon index of  $\sim 1.3 - 1.5$  at the same energy range. For the GRB 910402 during the time interval less than  $\sim 10$  s we observe drop of the hardness down to the value of  $\sim 0.1$  (fig.4). This value corresponds to the photon index of  $\sim 2.5 - 2.6$ . The moment of abrupt drop of the hardness corresponds to  $T_{ab} = 74 \pm 10$  s for GRB910402 (fig.4). For the burst GRB920723 the time of the abrupt drop of the spectral hardness down to  $\sim 0.1 - 0.2$  corresponds to the moment  $T_{ab} = 6 \pm 1$  s (fig.6). Thus the times of abrupt softening of the burst spectra  $T_{ab}$  coincide within statistical errors with the ( $T_1$ ) - beginning of the power law emission fading during afterglow for both GRB 910402 and GRB 920723.

Note that as one can see from fig.4 during the afterglow emission of the GRB910402 a statistically significant hardening of the spectra is observed. In the case of GRB 920723 the error bars are too large (fig.6) to make any conclusions about behaviour of the afterglow spectra.

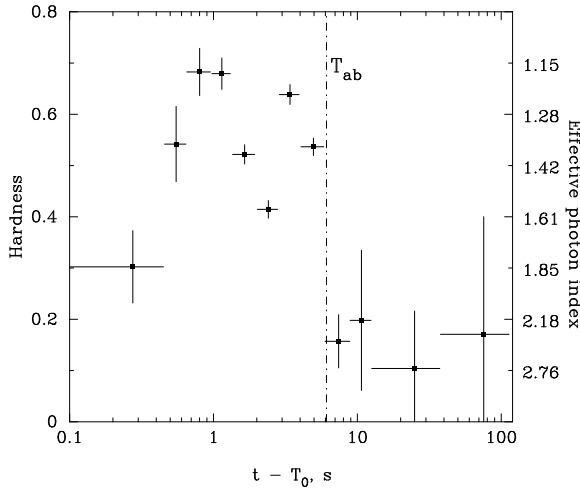
The afterglow emission intensities in 100 – 500 keV energy range are rather faint in comparison with gamma-ray bursts. Just a few tens of seconds after gamma-ray bursts discussed in this paper the afterglow intensities are  $\sim 1\%$  of the GRB maximum intensities. In the case of GRB 920723 the afterglow emission contains  $\sim 6\%$  of the total burst energy that was emitted during the interval of 6.1 – 700 s after  $T_0$  in the 100 – 500 keV energy range. In the case of GRB 910402 only  $\sim 1.6\%$  of the GRB energy was released during the observed afterglow (73.2 – 700 s after  $T_0$ ).

### 3. Conclusions and discussion

The PHEBUS instrument aboard the GRANAT observatory detected soft gamma-ray afterglow from the GRB 920723 and GRB 910402. These events are the brightest bursts detected by the PHEBUS instrument. In both cases the light curve of the burst makes smooth transition from the main burst into the afterglow emission (fig.3 and 5). The best fit power law indices of time for the afterglow are  $-0.70 \pm 0.04$  during 85 – 700 s af-



**Fig. 5.** The same as in the fig.3 but for the GRB920723



**Fig. 6.** The same as in the fig.4 but for the GRB920723

ter GRB 910402 and  $-0.60 \pm 0.05$  during  $8 - 700$  s after GRB 920723 (at  $1\sigma$  confidence level). In both cases the beginning of the afterglow emission ( $T_1$ ) coincides within statistical errors with the abrupt softening of the emission ( $T_{ab}$ ). Just after GRB event the energy spectrum of the afterglow emissions is much softer than the energy spectrum of the main GRB events. The average hardness ratio of the main GRB event (ratio of count rates in  $250 - 800$  keV to  $100 - 250$  keV) is equal to  $0.4 - 0.5$ . This corresponds to the power-law spectrum with the photon index of  $\sim 1.3 - 1.5$ . After abrupt transition to the afterglow both bursts have much softer spectra with the photon index of  $\sim 2.5$ .

Thus the moments corresponding to the beginning of domination of the emission fading as the power law during afterglow in both cases coincide within statistical errors with the abrupt softening of the energy spectra emitted by the both gamma-ray burst sources in soft gamma-rays ( $100 - 800$  keV).

that we found the moment when the much softer afterglow emission (connected with external shock) is starting to dominate over harder GRB emission (connected with internal shocks).

During the afterglow of GRB910402 the statistically significant hardening of the emission spectra is observed (fig.4). The afterglow spectrum just after the gamma-ray burst has the photon index of  $\sim 2.5$ . As one can see from fig.4 after  $\sim 200$  s the afterglow photon index was already  $\sim 1.6$ . This is the first observation of hardening of the afterglow spectra with time. The possibility of such hardening is under discussion in different GRB afterglow models.

The afterglow emission intensities in  $100 - 500$  keV energy range are rather faint in comparison with gamma-ray bursts. In the case of GRB 920723 the afterglow emission contains  $\sim 6\%$  of the total burst energy that was emitted during the interval of  $6.1 - 700$  s in the  $100 - 500$  keV energy range. In the case of GRB 910402 only  $\sim 1.6\%$  of the GRB energy was released during the observed afterglow in  $73.2 - 700$  s time interval.

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